TRANSIENT VOLTAGE PERFORMANCE OF VACUUM METALCLAD SWITCHGEAR

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ABSTRACT

The paper reports on an extensive program on switching voltage control carried out in conjunction with development of a new line of medium voltage vacuum metalclad switchgear equipment. The program covers switching transients, transient system analysis, investigation on transient parameters of system elements and vacuum breaker characteristics, computer studies and full-scale switching tests of medium voltage motor, dry type and liquid insulation transformers. Primary information is given on the different aspects of the program. The aim is to offer an overview of the extensive work rather than to treat the individual aspects in full detail.

The results of the program show that the new metalclad equipment will offer the advantages of vacuum switching technology without subjecting the system elements to more severe voltage stresses than presently encountered with "conventional" switchgear.

INTRODUCTION

For the past 15 years, vacuum circuit breakers have been used in medium voltage power systems. During this time a large number of breakers have been installed in a variety of networks and switching conditions. These applications have provided considerable operating experience and their performance has been good. However, in a few limited applications, namely arc furnace transformer switching,[2] and switching of motors under special conditions,[1] transient voltage problems were encountered. A number of papers have been published which offered explanations of the phenomena as well as solutions [3,4,5,6] for suppression of transient voltages.

The authors' company has undertaken an extensive development program to produce a new line of medium voltage metalclad equipment which will optimize the advantages of vacuum technology within a well controlled transient environment commensurate with air magnetic technology - today's standard of the industry. The intent of this paper is to present the most significant results of this program and offer an overview of its different aspects. Some of the more detailed aspects of the program analytical procedures are rather involved and it is the intent to publish these aspects separately so that it will be available for those interested in such background information.

SCOPE OF TRANSIENT VOLTAGE INVESTIGATION

To assure reliable transient voltage performance of the new metalclad equipment, the following steps were taken:

1. An In-depth Analytical Study of Vacuum Switching Transients

The purpose of this study was to further increase experience and understanding of basic vacuum switching phenomena so that they can be analyzed and controlled in complicated systems.

2. A Transient Systems Analysis of Different Systems and their Interaction with Specific Breaker Characteristics.

The purpose of this analysis was to identify potential transient voltage problem areas when applying vacuum breakers to a wide variety of medium voltage systems and to evaluate methods for controlling these transient voltages.

This part of the program had several theoretical and experimental aspects; namely, development of new methods of analysis and collection of transient data of typical system elements.

3. Transient Voltage Control Verification

The purpose of this portion of the investigation was to be sure that the vacuum metalclad equipment would create no transient voltages in excess of those specified by industry standards and practices. The final portion of the investigation was experimental verification of critical aspects by full-scale testing.

This paper will treat these three basic parts of the investigation.

SWITCHING TRANSIENTS

It may be useful to review briefly the transient phenomena associated with power switching. Transient switching voltages are dependent not only on switching device characteristics but also on the system configuration. These phenomena can be broadly classified in the following categories:

Capacitive-Current Switching Voltages

Capacitive-current switching has long been recognized as a a relatively arduous task for any kind of switching device. A recently published ANSI standard (application guide)[9] sets forth a criteria for acceptable transient voltage phenomena for the switching of capacitors via ac high-voltage circuit breakers. The new vacuum metalclad equipment being reported upon here meets these criteria in all respects.

Inductive-Current Switching Voltages

Switching of certain inductive circuits may produce significant transient voltages unless appropriate precautions are taken. The phenomena which may produce transient voltages are:

Current Chopping - True or Forced Chopping: Current chopping produces overvoltages if the breaker abruptly forces the current to zero rather than waiting for a natural current zero.[7] Chopping the current in a highly inductive circuit, such as the magnetizing current of an unloaded transformer, can produce relatively high transient voltages if not properly controlled.

The test program, carried out as a part of the new vacuum metalclad development, demonstrates that the transient voltages produced during current chopping are well below that tolerable to the most sensitive power system equipment including dry-type transformers and rotating machines.

Virtual Chopping - Induced Chopping or Simultaneous Interruption: A relatively new transient phenomenon has been identified and discussed in previous papers[2,4]. This is the phenomenon of "virtual chopping" which takes place when current is interrupted in one of the three phases and subsequently this phase restrikes thereby creating a relatively large pulse of high frequency current which in turn forces the current rapidly to zero in the other two phases. The resulting transient voltages may be similar to those which may occur during current "chopping".

Virtual chopping can occur only if the load current the natural frequency of the transient recovery voltage, the surge impedance of the bus bars, the additional capacitors on the system and the instant of breaker contacts parting with respect to the voltage wave, all simultaneously occur in a small sensitive region. It should be emphasized that for the phenomena to occur this whole set of very special conditions has to be met simultaneously, a condition which will be rarely met in practical systems using vacuum circuit breakers. Tests were made to create "virtual chopping" conditions and these tests demonstrated that the new metalclad equipment will maintain transient voltages to normal levels even in the presence of virtual current chopping.

Repetitive Reignitions or Short Arc Angle Phenomenon: Repetitive reignitions[3] may occur if the contacts of a circuit breaker part just shortly before a power frequency current zero. If the arc is extinguished while the contacts have a very small separation, the normal system transient recovery voltage will be impressed across this small contact gap, thereby increasing the likelihood that a restrike will occur and current will flow again. The restrike current may be of a high frequency oscillatory nature. If the circuit breaker interrupts this high frequency current, one or more restrikes may occur, thereby creating a succession of transient voltages increasing in magnitude as the separation of contacts increase. Many tests were conducted aimed at creating this "small arc angle" phenomenon. The results indicated that both the magnitude and the number of transient voltage surges are controlled by the new vacuum metalclad equipment to a level no greater that that created by conventional breakers which have been in use for the last decade.

TRANSIENT SWITCHING ANALYSIS

The transient analysis associated with the new vacuum metalclad development included the following types of system components:

a. Transformers, particularly dry type because of their low BIL.

b. Motors, because of their relatively low voltage withstand characteristics with respect to the rate of rise of voltage.

c. Special equipments, like arc furnaces, which can be highly inductive and with little damping of their transient voltages.

d. Capacitors.

This analysis consisted of both analytical and test work. The analytical work concentrated on methods of analysis and computer studies. These computer studies used the BPA transient analysis program augmented by other programs which were developed to meet the unique requirements of this investigation.

Methods of Analysis

The interactive phenomena between the breaker and different systems were scrutinized both analytically and by computer studies. The existing analytical methods had to be refined and expanded by:

1. developing a suitable circuit breaker model

2. improving representation of the system elements.

The circuit breaker model is programmed so that it is capable of repetitive action of restriking and clearing the transient currents depending on electrical stresses and quantities like di/dt at current zero as a function of other parameters. The input functions and data to represent the breaker characteristics were partially based on existing knowledge of vacuum interruption phenomena and partially on tests which were run for this purpose using the new vacuum metalclad equipment. The system element representation also required considerable analytical and development effort. It concentrated particularly on the development of a detailed transformer representation, the motor equivalent circuit for fast transients, and systems with cables.

Let us give just one example of the approach used in this region. Even though considerable work has been done in the physics of magnetizing current chopping, we have been able to refine this relatively old discipline. Not only the nonlinear transformer inductance was represented, but a significant advance was also made in the full representation of the dynamic hysteresis loop, being both frequency and initial conditions dependent. This has had a real practical impact. On one hand, it expressed appropriately the damping of the electro-magnitic transients. On the other hand, it put the voltage concepts in new light. Details of this new analytical approach will be presented later in a technical paper.

Transient Parameters of Systems - Measurements Program

Even the best methods of analysis with proper equivalent diagrams for system representation can turn into a highly inaccurate tool if the input data or transient parameters of system elements are not sufficiently accurate. Transient parameters relate to surge impedances and propagation factors at different frequencies, inductances at these same frequencies, and stray capacitances. The attenuation factors at different frequencies are of particular importance since they have a direct influence on voltage amplitude. Unfortunately, the data on equipment transient parameters is very scarce. This particularly applies to dry-type transformers and transient parameters of motors. To get the necessary information, a special measurement program had to be conducted which also provided confirmation of the accuracy and adequacy of component representations. Detailed measurements were made on:

1. dry-type and liquid-filled transformers of 4.16 kV and 13.8 kV 1000 kVA.

2. 4.16 kV induction motors 350 hp and 3000 hp.

3. a relatively typical 4.16 industrial system.

The transient parameters of these devices and systems were measured using a low-voltage-current pulsing method.[6] The equivalent capacitance was evaluated from oscillograms as in Figure 1, where the natural frequency was measured with different values of added capacitance at the terminals. Similarly the dependence of other transient parameters on frequency was measured. The surge impedance was also measured by terminating the circuit with different values of resistance. Single-phase circuits were measured as well as appropriate three-phase configurations for both the first pole and also the last

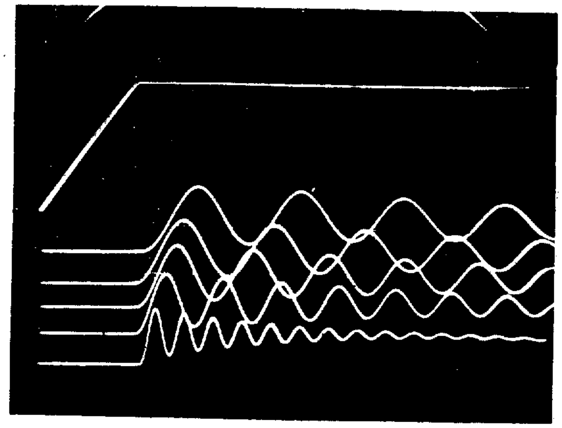

Figure 1. Measurements of motor transient parameters at different frequencies

Upper trace: 60 Hz current interruption

Lower traces: Transient voltage responses to current interruption for different values of terminal capacitances.

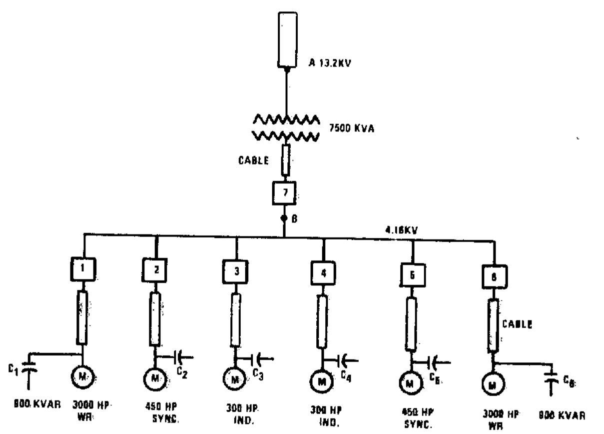

Figure 2. Industrial power system used for transient phenomena investigations.

pole to interrupt the current.

On the transformers, the measurements of the magnetic dynamic characteristics were also made. The motors were measured both with the rotor in and out of the stator to arrive at the proper representative circuit. Furthermore, the measurements of 60 Hz inductances and total capacitances were performed by conventional methods to arrive at the correlation between parameters at power frequency and at natural frequencies. In addition to the above, the transformer and motor manufacturing departments performed transient measurements on their respective products to obtain values across a range of product ratings.

A 350 hp motor was equipped with taps at the initial turns of the first three coils so that the voltage stresses during the switching transients could be measured at these important points. These measurements were made using the low-voltage pulsing technique as well as under prestrike conditions during power tests.

The industrial system shown in Figure 2 was subjected to transient measurements using again the low-voltage pulsing method. Figure 3 shows the following events: 60 Hz current zero, transient recovery voltage, and restrike with the restart of 60 Hz current. These phenomena together with currents in the other phases of the system were measured with even higher resolution so that the transient parameters could be properly evaluated. Attention was paid to the effect of cables and particularly to evaluation of damping factors of the transients. To obtain proper damping for the computer studies the above measurements were made on a total of 22 circuit conditions and connections of the basic diagram of Figure 2. The agreement of the computer plots with the oscillograms from the measurements was very good.

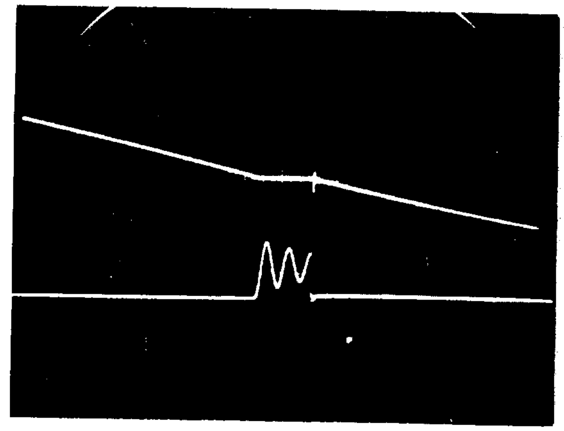

Figure 3. Current and voltage waveshapes during interruption and subsequent restrike. Sweep 400 us/Div.

TRANSIENT VOLTAGE CONTROL VERIFICATION

Knowledge of switching transients, breaker characteristics, transient responses of system elements and their mutual interaction permitted appropriate evaluation of transient voltage control methods relative to the design of the new metalclad equipment. The performance of the equipment was checked analytically and by computer studies but the final check was made by full-scale testing.

The testing efforts, on which a brief report is given here, can be divided into two basic categories:

- capacitive current switching tests
- inductive current switching tests

The verification of capacitive current switching performance was based on a large number of full-scale tests. These tests may be considered routine. The special inductive current switching tests, on the other hand, can hardly be classified as routine. Therefore, a brief account of the test circuits, test procedures and measurements is given.

Test Circuits

Tests were conducted by switching actual load components using transformers or motors rather than using substitute circuits composed of inductances and capacitances. This gives the advantage of actual system parameters, including the nonlinearities of its elements. The ratings of the switched transformers and motors were selected so that they would be in the region which would produce the highest transient

Tested Object	Test Conditions	Basic Circuits	No. of Test Circuits
Transformer dry type 1000 KVA	NO LOAD magnetizing current interruption	Figure 4a	4
	NO LOAD inrush current interruption and closing transients	Figure 4a	1
	LOAD 0.6 power factor	Figure 4b	3
Transformer oil insulation 1000 KVA	NO LOAD magnetizing current interruption	Figure 4a Figure 4c	4 5
	NO LOAD inrush current interruption closing transients	Figure 4a	2
	LOAD 0.7 power factor	Figure 4b Figure 4d	2 3
Induction motor 350 HP	STARTING closing transient starting current interruption	Figure 4e Figure 4f	10 5
	RUNNING No load	Figure 4	2

TABLE I

Rated Voltage		4.16 kV_{rms}	13.8 kV_{rms}
Metalclad Equipment	Peak switching voltages produced by the new vacuum metalclad	10 kV	30 kV
	BIL	60 kV	95 kV
Lightning Arrester	Rating	4.5 kV	15 kV
	Sparkover	15 kV	40 kV
Transformer BIL	Liquid Insul. Power	75 kV	110 kV
	Liquid Insul. Distribution	60 kV	95 kV
	Dry Type	25 kV	50 kV
Motors	1.25 X HIPot	16.5 kV	50.6 kV

TABLE II

voltages. Based on this work we feel that the extrapolation to other ratings can be done reliably.

A dry-type transformer rated 4.16 kV/480 volts, 1000 kVA, and a liquid-filled transformer rated 13.8 kV/480 volts, 1000 kVA, were tested under conditions of no-load current, magnetizing inrush current, and also with low power factor loads. In addition a 4.16 kV, 350 hp induction motor was tested under starting and no-load running conditions. The tests were made with and without a cable as shown in Figure 4. The available short-circuit duty of the supply circuit was also varied to produce 130, 230, 320, 500 and 750 MVA by adjusting the circuit inductance. The capacitances C_1, C_2, and C_3 were changed to represent different system conditions, in the range from 0.2 uF grounded to 10 uF ungrounded. The latter represented a small power factor compensation capacitor bank on the bus bars necessary to achieve the virtual chopping conditions. Thus a number of test circuits were used, each a variation of the appropriate basic circuits of Figure 4A to 4F. A total of 41 different circuit modifications was used as shown in Table I. A number of tests were then made using each of the 41 circuits.

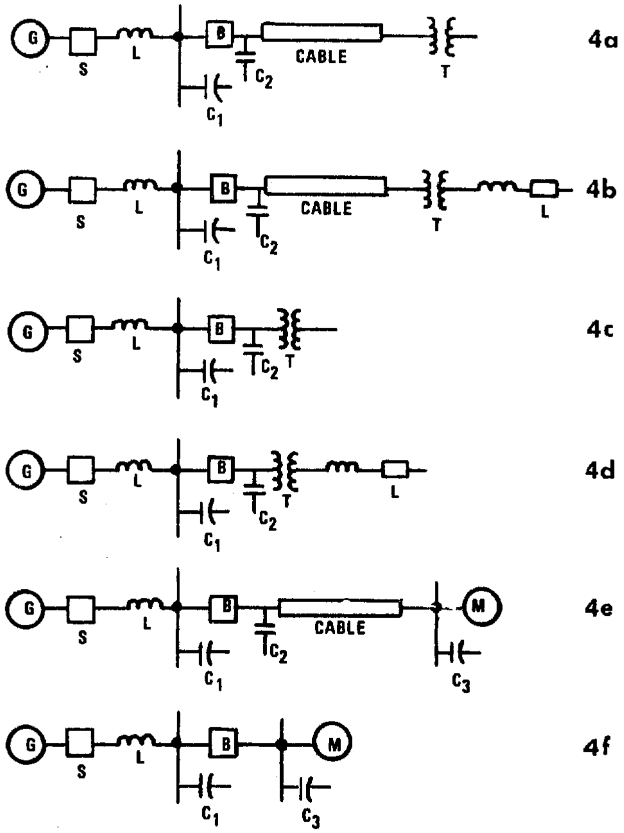

Figure 4. Basic test circuits

Test Procedure

The test procedure concentrated on both the closing and interruption transients. Most of the tests were made as "C-O" duty with both operations recorded. With each test circuit (last column of Table I) a series of tests was performed. Each series generally consisted of a number of tests where contact separation differed by 20° over a half cycle. In the critical regions the contact separation was controlled by 5° increments and the number of tests was repeated to cover the statistical spread. Similarly the closing impulse was controlled so that the prestrike would occur to produce the worst transient voltage condition.

Careful adjustment to identify the most severe condition and repetition of tests in this region were important aspects of this program. This procedure cuts down the number of tests which otherwise would be required on a statistical basis to cover the entire range. Additional tests were made to assure that there would not be an unexpected performance in a non-critical region. This was the purpose of performing tests with contact separation differing by 20° over a half cycle. Even these tests were repeated several times to be sure that statistical deviations do not mislead our interpretation of the results.

It should be pointed out that at times it was extremely difficult to arrive at the desired phenomenon which was known to exist theoretically. For example, even under carefully controlled conditions, it was very difficult to create virtual chopping even with the circuit properly adjusted by capacitances C_1 and C_2 (see Figure 4) and timed for worst conditions of contact separation.

Switching Test Measurements

Sophisticated measuring methods were employed to reliably record the fast transients. Some of the oscillographic equipment was placed in close proximity to the test equipment in order to obtain true frequency response up to 10 MHz. Special techniques of screening, voltage divider compensation and balance for differential measurements had to be employed. The capacitance of the voltage dividers at the transformer was held to the order of 1% of transformer stray capacitance in order to obtain true transient voltage.

The following measurements were taken:

1. $V_{S_{a-b}}$ breaker source side voltage, line-line, one phase only

   $V_{L_{a,b,c}}$ breaker load side voltages, line-ground, phases a,b,c

   $I_{a,b,c}$ currents through the breaker, phases a, b, c, contact travel, closing impulse, timer

2. Cathode ray oscillograph #1
   3 beam, mechanical sweep 20 us/mm:
   $V_{T_{a,b,c}}$ transformer or motor line-ground voltages, phases a,b,c

3. Cathode ray oscillograph #2
   3 beam, mechanical sweep 20 us/mm:
   $V_{B_{a,b,c}}$ voltages across breaker, phases a,b,c

4. Tape recording equipment
   13 channel, replay sweep to 10 us/mm:
   $I_{a,b,c}$ breaker currents, phase a,b,c

   $V_{s\ a,b,c}$ breaker source side voltages, line-ground, phase a,b,c

   $V_{T_{a,b,c}}$ transformer or motor voltages line-ground, phase a,b,c

   $V_{T_{2,c}}$ transformer secondary voltage, line-ground, phase c

   $V_{T,\ b-c}$ transformer line-line voltage

5. Tektronix, 2 beam, sweep 100 us/Div.

   V_{Ta} transformer or motor voltage line-to-ground, phase a

   I_a breaker current phase a

6. Tektronix, 2 beam sweep to 0.5 us/Div.
   V_{Ma} motor voltage of winding a

   V_{1a} coil or turn voltage

Test Results

A vast amount of data was accumulated during the test program. This data was analyzed to evaluate:

- The overvoltage performance of the new equipment under many different test conditions.
- The transient responses of the system under different switching conditions.
- The characteristics of the switching equipment and their interaction with the system.

The first item offers direct guidance to applications of the equipment with respect to systems similar to test circuits.

The last two items are of importance in supporting the understanding of the phenomena. They provided further data for analytical studies. This is essential for extrapolating the test results to other circuits and for providing the confidence in performance of the equipment over the whole range of applications.

It was concluded that the transient voltage performance of the new equipment was found very good over the entire range of explored areas, namely:

1. Prestrike during motor and transformer energizing.
2. Chopping of transformer magnetizing, inrush and load currents together with motor starting and no load motor currents.
3. Virtual chopping of inductive loads.
4. Repetitive reignitions under a wide range of switching conditions.

Test results show that in the above areas the transient voltages are limited to values no higher than presently found in comparable medium voltage systems.

As an example, Figure 5 shows the typical trensient voltages from chopping the inrush current of the 4.16 kV, 1000 kVA dry-type transformer during a close-5 cycles - open test. This operation is highly unusual in a practical system, but it could produce the most severe transient voltage condition for current chopping. The chopping wave shapes are well pronounced, however, the maximum transient peak voltages were only 7.4, 7.8, 7.2 kV in the different phases and without repetitive reignitions. Permissible voltage peaks would be in the order of 18 kV (75 percent of the dry-type transformer BIL).

The test results can be summarized by giving the maximum switching over-voltages produced by the new metalclad equipment under the most severe conditions in 4.16 and 13.8 kV systems. These values are shown in Table II together with other transient voltage characteristics of associated system elements for comparison purposes. Test results also confirm that the transmission of switching voltages to the secondary side of the transformer follows directly the inductive transformation ratio. Therefore, with the maximum voltages as given in Table II, the secondary circuits are also free of transient voltage hazards.

More detailed results of this investigation will be presented in subsequent papers. Suffice to state here that analytical and test results are in good agreement.

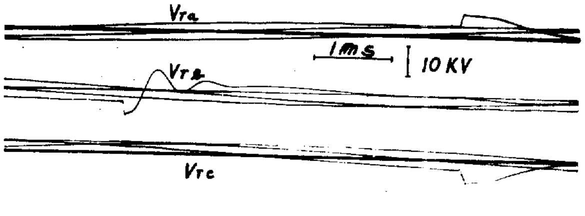

Figure 5. Transformer (4.16 kV, dry-type) line to-ground voltages during chopping of inrush currents.

CONCLUSIONS

The goal of this investigation was to aid in the development of a family of medium voltage metalclad equipment which takes advantage of vacuum switching technology while at the same time subjecting medium voltage equipment to transient voltages no greater than those encountered in today's systems.

This investigation shows that the above goals have been met.

Results of full-scale tests and system analyses are in good agreement. Methods of system analyses were advanced and switching transient phenomena understood so that there is full confidence that the voltage stresses caused by vacuum breaker switching in industrial systems would not be greater than those encountered during these tests.

Therefore it may be concluded that the transient voltage surges produced by the new vacuum metalclad equipment are so controlled that motors, dry-type transformers, liquid-filled transformers, lightning arresters and cables may be applied without additional investigations or precautions.

Acknowledgement

We wish to acknowledge the significant contributions to the described program made by Dr. S. Ihara, particularly in the area on computer studies, equivalent circuits, and experimental work; Mr. E. Tuohy in the area of electromagnetic transient, transformer and motor switching; Dr. C. Kang in advanced measurements.

REFERENCES

(1) T. Itoh, et.al: Voltage Escalation in Switching of Motor Control Circuit by Vacuum Contactor AIEE Transactions (PAS) Vol.91, pp.1897-1903, No.5, Sept/Oct. 1972.

(2) J. Panek, K. Fehrle: Overvoltage Phenomena Associated with Virtual Chopping in Three-Phase Circuits IEEE Trans. (Vol. PAS-94), No.4, pp.1317-1325, July/Aug. 1975.

(3) A. N. Greenwood, D. R. Kurtz, J. C. Sofianek: A Guide to the Application of Vacuum Circuit Breakers IEEE Trans. (Vol. PAS-90), pp.1589-1997, July/Aug. 1971.

(4) M. Murano, et al: Three phase Simultaneous Interruption in Interrupting Inductive Current with Vacuum Switches IEEE Trans. (Vol. PAS-93) No.1, pp.272-280, Jan/Feb. 1974.

(5) Y. Murai, et al: Protection of Motor From Switching Surge by Vacuum Switch 1974 IEEE PES Winter Meeting paper T74-174-9.

(6) M. Okawa, M. Koike: Switching Surge and Application of Vacuum Switching Device 1974 IEEE PES Winter Meeting, paper C74-173-1.

(7) T. H. Lee: Physics and Engineering of High Power Switching Devices Book, MIT Press 1975.

(8) A. N. Greenwood: Electrical Transients in Power Systems Wiley-Interscience, 1971, Book.

(9) ANSI C37.0731-1973; IEEE Std. 342-1973.

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